A MULTI-POLE MAGNETIC GENERATOR WITH ENHANCED VOLTAGE OUTPUT FOR LOW-FREQUENCY VIBRATIONAL ENERGY HARVESTING

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Abstract: This paper presents a vibrational energy harvesting approach using an array of alternating magnetic poles to enable frequency up-conversion and high-amplitude voltage output under low-frequency mechanical excitation. This approach is intended to overcome the low voltages typically found in magnetically-based energy harvesters. A mesoscale (4.6 x 5.4 x 1.5 cm^3) prototype device was tested under low frequency (< 15 Hz) excitation to mimic human-induced motions. At an excitation of 0.8 g at 9.25 Hz, an electrical frequency quadrupling was achieved along with a nonlinear voltage boost up to 2 V_{pk} (0.87 V_{rms}). These results demonstrate the potential for voltage enhancement using multi-pole magnetic generators.

Key words: magnetic vibrational energy harvester, low frequency, frequency up-conversion, voltage boost

1. INTRODUCTION

Passive energy harvesting from human motion or mechanical vibrations is of great interest for portable electronic devices [1]. Piezoelectric, capacitive, and magnetic transduction mechanisms have all been explored for extracting electrical energy from mechanical motion [2]. Of these, magnetically-based (electrodynamic) transduction is well-suited for low-frequency, large-amplitude vibrations, particularly for human-induced motions. However, it is well known that magnetic generators typically generate low-amplitude voltage output in comparison to piezoelectric or capacitive generators.

The low voltage and low frequency output of a magnetic generator presents significant challenges for voltage rectification and power processing [4], since active and passive bridge rectification circuits exhibit low efficiencies for voltages less than 0.5 V. The voltage can be passively amplified using a transformer, but the low-frequency signals typically encountered for energy harvesting (usually <200 Hz) demand prohibitively large transformers to achieve sufficiently large magnetizing inductances.

In the present work, a magnetic array is explored for use in a magnetic generator to boost both the amplitude and frequency of the output voltage. The goal is to theoretically and experimentally demonstrate voltage enhancement, quantify the improvement, and investigate the practical and technological limits for such an approach.

2. THEORY

2.1 Magnetic Induction

In a magnetic linear generator, the voltage induced in the coil is given by Faraday's Law

$$V = -N\frac{d\Phi}{dt}, \qquad (1)$$

where N is the number of coil turns, Φ is the flux in the coil, and t is time. In order to increase the induction voltage, a large number of turns is desired for the coil, and high frequency, high amplitude relative motion is desired between the coil and the magnet to increase the time rate change of the flux. However, the design of a real system imposes substantial constraints for increasing N or $d\Phi/dt$..

First, there is practical limit to the number of coil turns because of space constraints or manufacturing limitations. Additionally, the frequency and amplitude of the source vibration are set by the application. Consequently, a vibrational energy harvester (modeled as a second-order spring-mass-damper) is usually designed such that the system resonance occurs at or near the vibration frequencies with the most energy content, typically below 200 Hz. At resonance, the amplitude of the mechanical oscillation is limited by the total electromechanical damping or, for large amplitudes, by the maximum stroke length allowable within the device. In essence, the motional dynamics (frequency, amplitude, velocity) are determined by and constrained by the source vibration and size of the physical system.

The only remaining design variable is the magnetic flux—the product of B-field and surface area. The surface area is again limited by space, and the magnitude of the B-field is material limited by the permanent magnets. What remains is the option to create multiple flux fluctuations within one mechanical cycle. This can be achieved by using multiple magnets with dimensions smaller than the oscillation amplitude. This idea is analogous to using multiple poles in a conventional rotating synchronous machine. To first-order, increasing the number of poles can boost the voltage (at the expense of current), but the power remains relatively constant (assuming a fixed conductor volume). These effects are explored in the context of a linear vibrational energy harvester.

2.2 Multi-pole Magnetic Array

In order to create multiple flux fluctuations during each mechanical stroke, a multi-pole magnetic structure is proposed where more than one magnet is used to form a linear array of alternating magnetic poles. The pole pitch (linear distance between N and S poles) must be smaller than the stroke length for this method to offer any practical benefit. Accordingly, rather than one large coil, multiple smaller coils are required, one for each magnet pole. The multi-pole magnetic array configuration considered in this paper is illustrated in Fig. 1.

In such a configuration, although the total magnetic flux in each coil is reduced with the pole pitch, the flux switching frequency is increased by the same factor (assuming the motion of the magnet array is the same). This scaling assumes the average B-field through the coil is constant irrespective of the magnet area, or at least this flux-density has a weak dependence on the surface area. If this is the case, the $d\Phi/dt$ of each individual small coil will equal that of one large coil. If the small coils are connected in series, the voltage amplitude should be boosted by this amplification factor. In addition, the electrical frequency will also increase, benefiting any passive amplification schemes.

While these effects are well known for synchronous rotating machines, e.g. PM generators, those machines operate at a constant speed in one direction. For a linear generator, the impact of the time-varying oscillatory velocity and the end coils (those that do not overlap with the magnet array at all times) is not so clear. Thus, simulations and experiments were conducted to elucidate these effects.

2.3 Simulation

To investigate the multi-pole configuration, quasi-static magnetic simulations were performed based on the following assumptions (illustrated in Fig. 1):

a. An array of magnets (with a total size of 1.27 cm x 2.54 cm x 0.953 cm with varying number of poles) moves sinusoidally with respect to a set of coils with a peak amplitude of 1.27 cm and mechanical frequency of 10 Hz.
b. The air gap between the magnet array and coils is fixed at a value between 0.5 and 2 mm.
c. There are no lateral gaps between magnet poles, and no soft magnetic back irons.
d. Single-turn series-connected filamentary coils circumscribe and oppose each magnet pole.

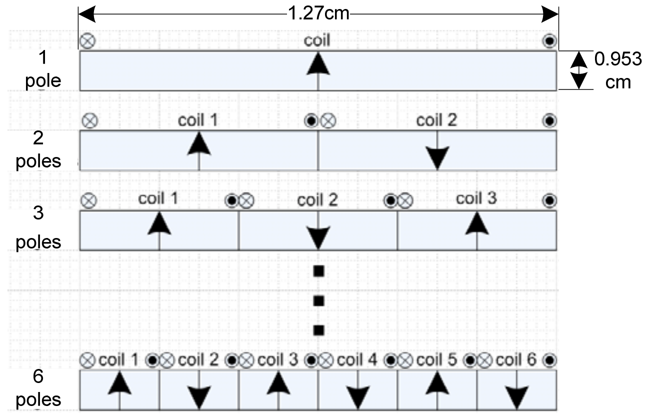


Fig. 1: Schematic cross-section of magnetic array simulation (extends 2.54 cm out of the plane).

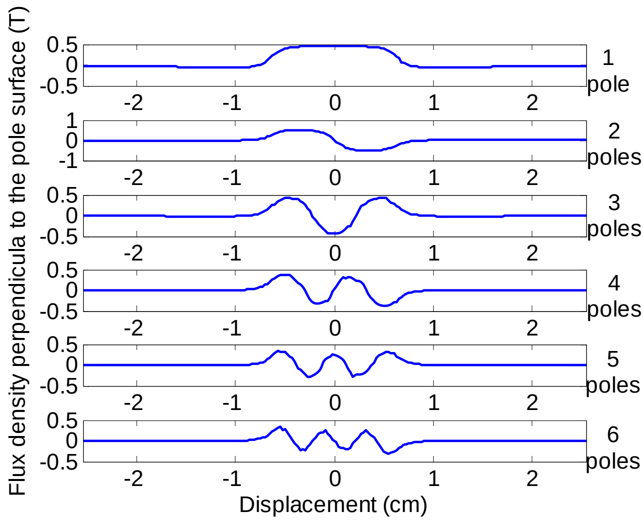


Fig. 2: Flux density profiles of array configurations with 1-6 magnets (1mm air gap).

First, 3-D finite element analysis was utilized to determine the midline perpendicular B-field profiles of the different magnet array configurations as shown in Fig. 2. Then, the time derivative of the flux was calculated to obtain the induced open-circuit voltage waveforms, as shown in Fig. 3. Frequency multiplication can be observed as the number of magnets increases. In Fig.4 (a), the RMS voltage vs. number of magnet poles is plotted with different air gaps. The trend for voltage enhancement depends strongly on the air gap. A smaller air gap offers the potential for large voltage enhancement. For larger air gaps, the magnet-coil flux linkage tends to decrease as the number of poles is increased, indicating a limited voltage boost. The peak voltage enhancement tends to occur when the pole pitch is 3-3.5x the air gap. Fig. 4 (b) shows the effect of displacement amplitude on the RMS voltage of a 4-magnet array. Nonlinearity can be observed as the amplitude increases.

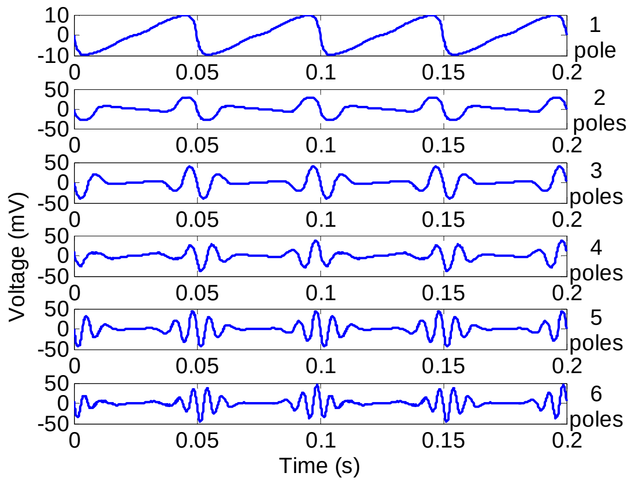
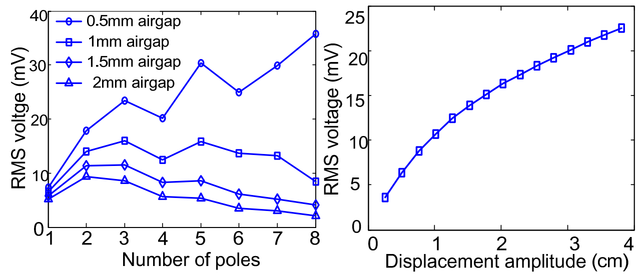


Fig. 3: Open circuit voltage waveforms of array configurations with 1-6 poles (air gap of 1mm).



(a) (b)

Fig. 4: (a) RMS voltage vs. number of poles with different air gaps. (b) RMS voltage vs. displacement amplitude (4 poles; 1 mm air gap).

3. EXPERIMENTAL

3.1 Device Design

In conjunction with the simulations, a mesoscale test generator was fabricated to demonstrate the idea. The device structure and schematic is shown in Fig. 5. A sliding translator plate contains four individual magnets (0.32 cm x 2.5 cm x 0.64 cm) arranged with alternating N and S pole magnetizations. The pole pitch is 0.38 cm, slightly smaller than the magnet width of 0.32 cm because of a small spacer between each magnet. Four, series-connected 300-turn coil windings are mounted on the stator with a gap of 1 mm between the magnets and coils. A ball bearing slider is used to constrain the motion to one linear degree of freedom, and a set of repelling magnets on the translator and the stator create a "magnetic spring" at the base. For testing, the structure was oriented and vibrated vertically, so that the translator mass oscillated against the repulsive force of the magnetic spring.

As opposed to conventional designs that utilize a mechanical coil spring [5] or cantilever beam [6], this structure affords a large-stroke, low-frequency, single degree of freedom motion in a compact form factor, while maintaining a small air gap between the magnets and coils without rubbing. Additionally, the very strong repulsive forces as the spring magnets approach one another creates non-contact end-stops. The ability to avoid mechanical collisions at high velocity avoids the large dissipative energy losses associated with mechanical end stops.

One issue for this design, however, is the nonlinearity introduced by the magnetic spring. For the experiments here, this nonlinearity causes the mechanical resonant frequency to increase with increasing excitation amplitude, thus complicating the interpretation of the results. However, in practice, this nonlinearity may actually improve the overall performance [7].

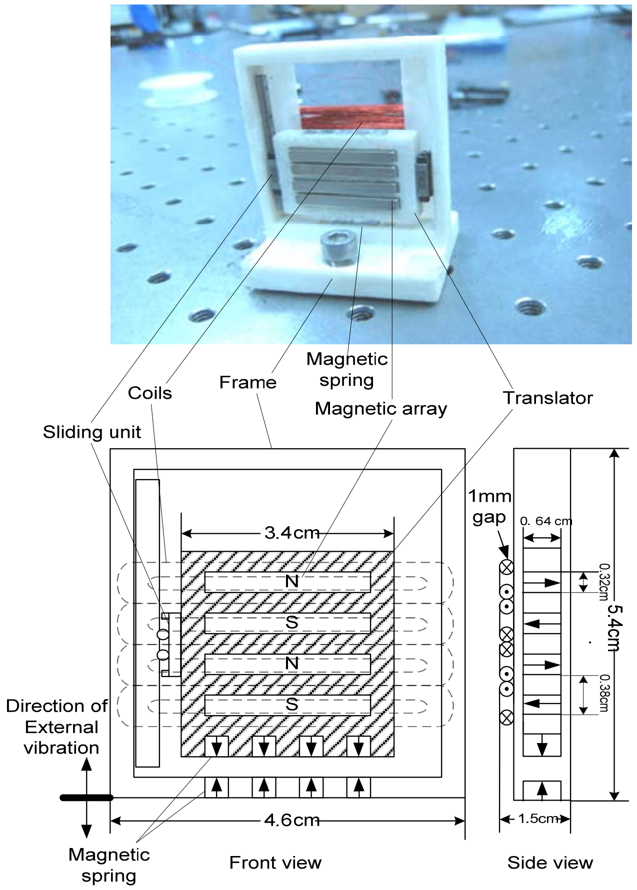


Fig. 5: Picture and schematic of the prototype.

3.1 Device Testing

The device was tested using a mechanical shaker to sinusoidally excite the frame under three excitation levels: 0.2 g, 0.5 g, and 0.8 g. Different peak output frequencies (13 Hz, 11.1 Hz, and 9.25 Hz, respectively) were observed at the different amplitudes, a consequence of the nonlinear magnetic spring. The waveforms and spectra of the open-circuit voltages are shown in Fig. 6. Frequency multiplications and nonlinear voltage increases are apparent as the excitation level increases with the rms voltage increasing nonlinearly from 68 mV up to 870 mV. Additionally, a complete frequency up-conversion is seen in the FFT data for the 0.8 g case.

A swept sine test was performed to examine the frequency response of the system. Fig. 7(a) shows the RMS open-circuit voltage for a 5-15 Hz frequency sweep at a constant 0.8 g. As compared to the narrow-band frequency responses of typical linear-spring energy harvesters, a broadband frequency response is observed with a -3dB bandwidth of 4 Hz around the 9.25 Hz peak. This broad frequency bandwidth is a result of the slider/magnet spring construction, and offers large output power levels over a range of frequencies.

Finally, different resistive loads were attached to the coil to find the maximum output power. Fig. 7(b) shows the output power is relatively insensitive to resistive loads from 200-500 Ω with a maximum of 0.55 mW at 400 Ω. The reason for this load insensitivity has not been fully explored.

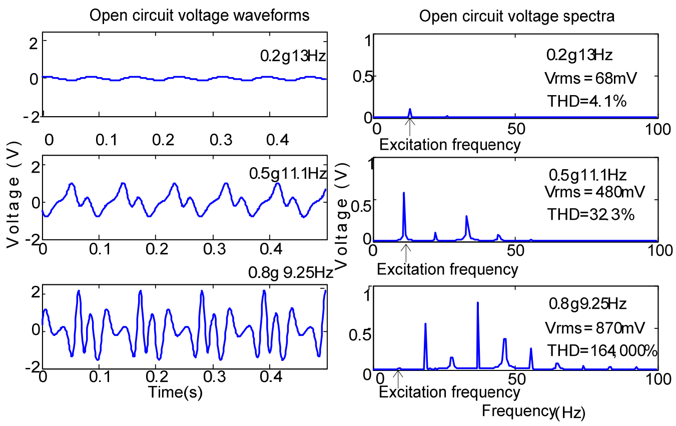
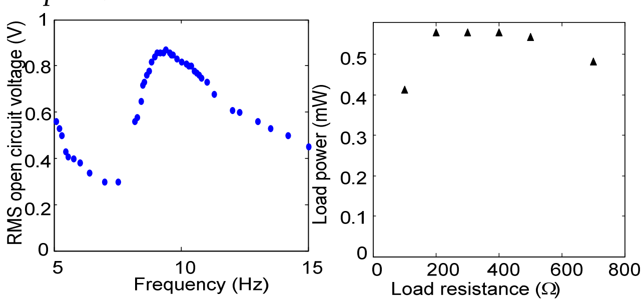


Fig. 6: Open-circuit voltage waveforms and frequency spectra showing voltage enhancement and frequency multiplication with increasing excitation level. Rms voltage and total harmonic distortion (referenced to the input waveform frequency) are summarized within the plots.



(a) (b)

Fig. 7: (a) RMS open-circuit voltage vs. excitation frequency at 0.8 g and (b) Load power vs. load resistance at 0.8 g and 9.2 Hz.

4. CONCLUSION

The paper theoretically and experimentally demonstrates an effective multi-pole magnetic design for boosting the output voltage amplitude and frequency for magnetic vibrational energy harvesters. A magnetic energy harvester construction was also introduced—using a linear slider and a magnetic spring—to afford the high stroke and low frequency performance necessary to demonstrate the idea on the mesoscale. The power level and overall performance can be further improved by optimizing the design parameters, including the dimensions of the magnets and spring magnets, number of coil turns, etc. Moreover, this method can be extended to achieve larger frequency and amplitude enhancement factors by employing magnet arrays (possibly microfabricated) with smaller pole pitch. Additionally, this multi-pole approach can be applied to both linear and rotary type vibration converters.

There are several limitations that will limit the voltage enhancement. First, the air gap between the coil and the pole surface is a critical parameter. As the pole pitch is reduced, the magnetic fields tend to loop back into neighboring poles rather than interacting with the coils. As predicted by the simulation and loosely demonstrated experimentally, the air gap should be about 1/3 the pole pitch for effective inductive coupling and voltage boost. Second, reducing the air gap without causing mechanical contact requires precision manufacturing. If good air gap control can be achieved, the potential exists for further reducing the magnet pitch to sub-millimeter microfabricated magnet poles for further voltage enhancement.

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